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Accelerator Physics

Lecture 2 of 2

Rende Steerenberg – CERN

Topics for Today

- Longitudinal Motion
- Some of the Possible Limitations
- On the Way to HL-LHC…

Longitudinal Motion

Motion in the Longitudinal Plane

- What happens when particle momentum increases in a constant magnetic field?
  - Travel faster (initially)
  - Follow a longer orbit
- Hence a momentum change influence on the revolution frequency

$$\frac{df}{f} = \frac{dv}{v} - \frac{dr}{r}$$

- From the momentum compaction factor we have:

$$\frac{\Delta r}{r} = \alpha_p \frac{\Delta p}{p}$$

- Therefore:

$$\frac{df}{f} = \frac{dv}{v} - \alpha_p \frac{dp}{p}$$

Revolution Frequency – Beam Momentum

$$\frac{df}{f} = \frac{dv}{v} - \alpha_p \frac{dp}{p}$$

$$\frac{dv}{v} = \frac{d\beta}{\beta} \Leftrightarrow \beta = \frac{v}{c}$$

From the relativity theory: $p = \frac{E_0 \beta \gamma}{c}$

We can get: $\frac{dv}{v} = \frac{d\beta}{\beta} = \frac{1}{\gamma^2} \frac{dp}{p}$

Resulting in : $$\frac{df}{f} = \left[\frac{1}{\gamma^2} - \alpha_p\right] \frac{dp}{p}$$

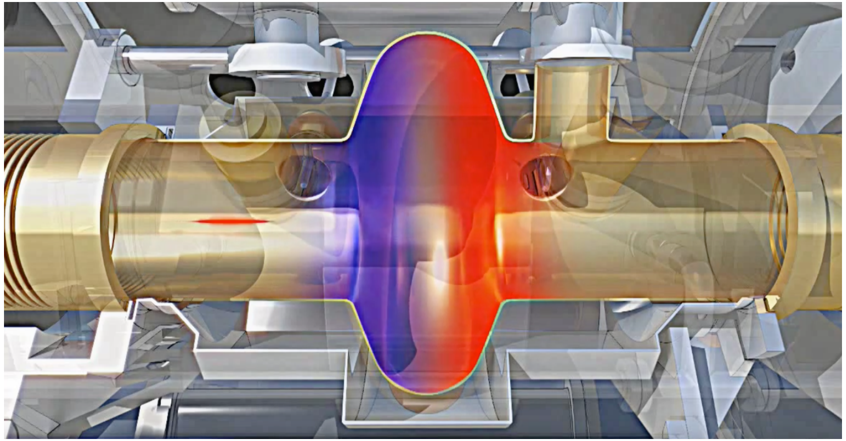
Transition

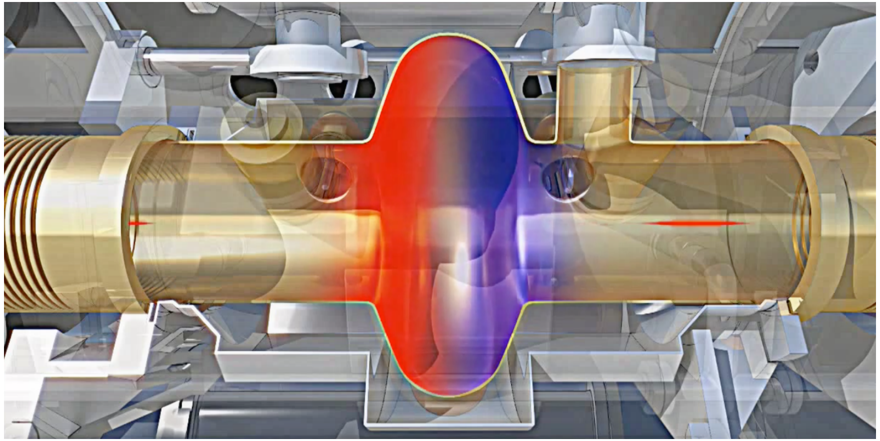
$$\frac{df}{f} = \left[\frac{1}{\gamma^2} - \alpha_p\right]\frac{dp}{p}$$

- Low momentum (β << 1 & γ is small) → $\frac{1}{\gamma^2} > \alpha_p$
- High momentum ($\beta \approx 1$ & γ >> 1) → $\frac{1}{\gamma^2} < \alpha_p$
- Transition momentum → $\frac{1}{\gamma^2} = \alpha_p$

RF Cavity Workings

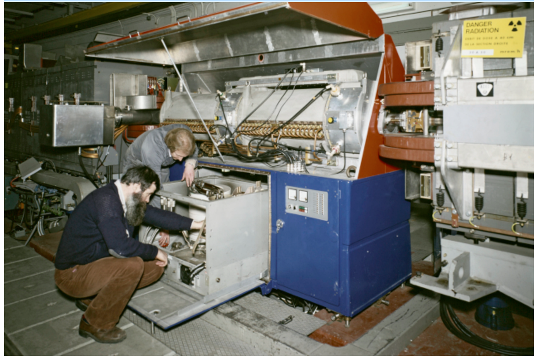
- Charged particles are accelerated by a longitudinal electric field
- The electric field needs to alternate with the revolution frequency



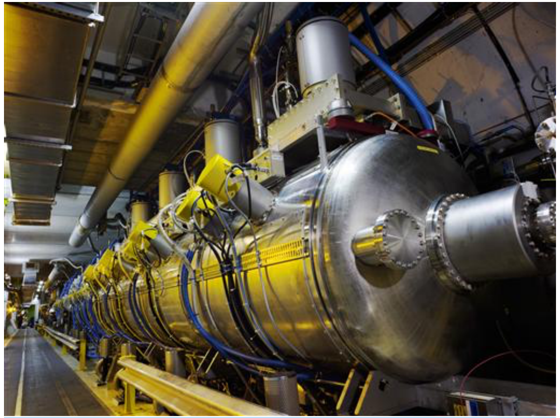


RF Cavities

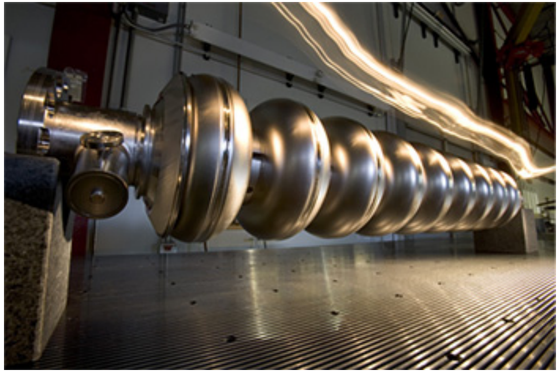
PS variable frequency cavity



SPS 200 MHz fixed frequency Cavities

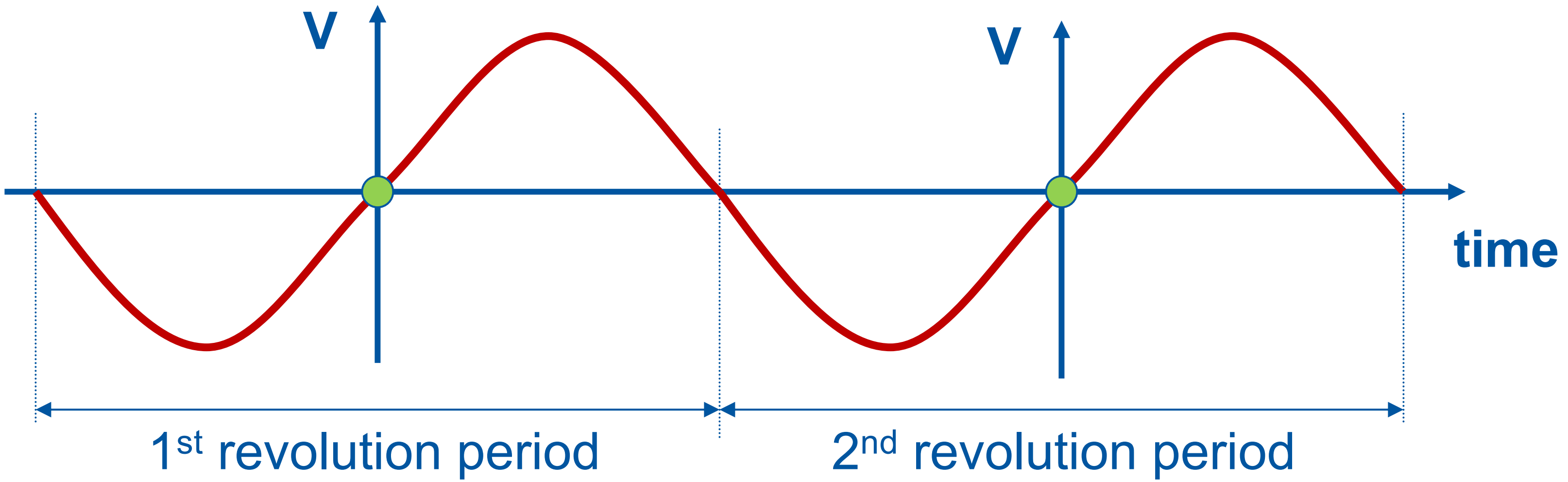


Super conducting fixed frequency LHC cavity

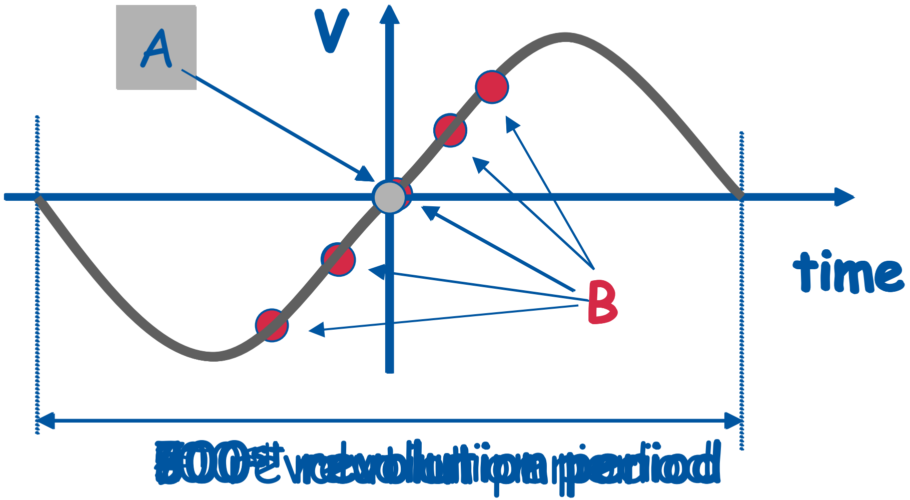


Low Momentum Particle Motion

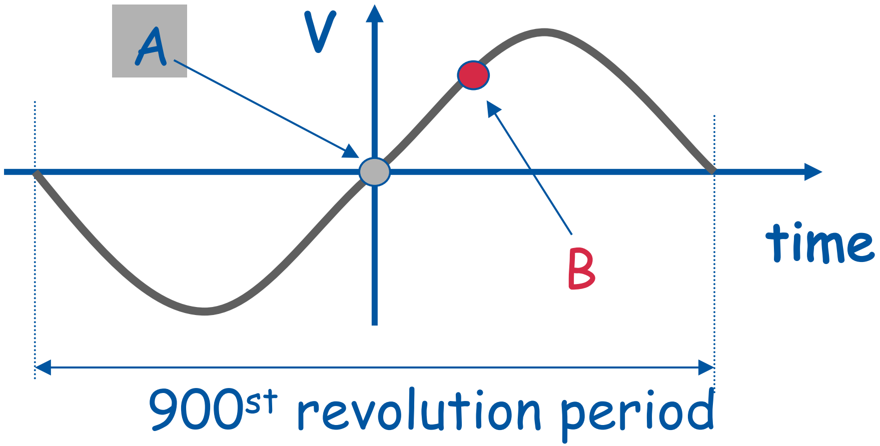
- Let's see what a low energy particle does with this oscillating voltage in the cavity



Longitudinal Motion Below Transition



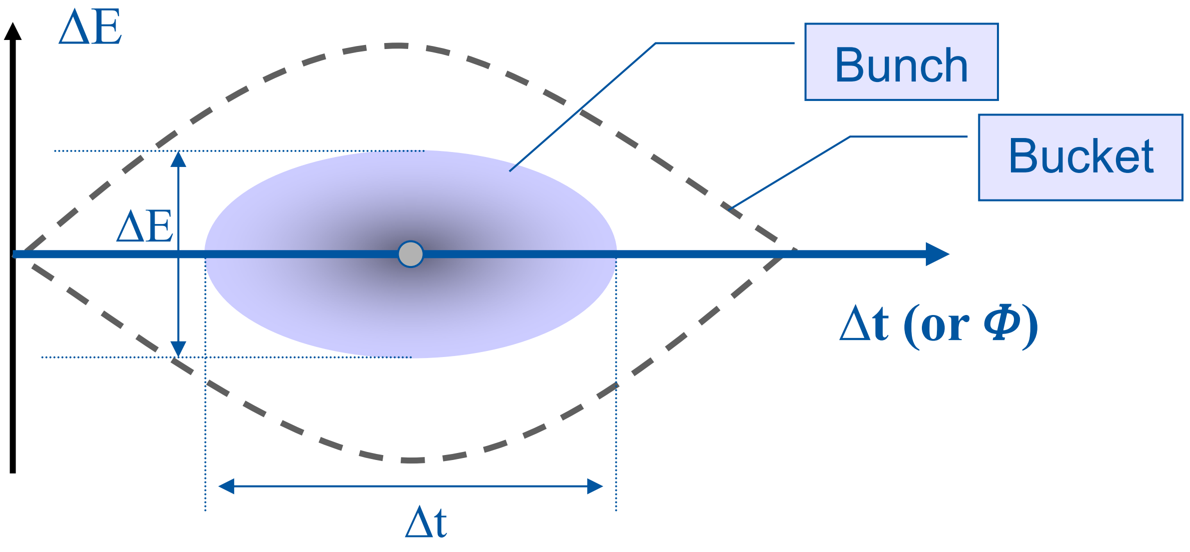
…after many turns



- Particle B has made 1 full oscillation around particle A
- The amplitude depends on the initial phase

- These are **Synchrotron Oscillations**

Stationary Bunch & Bucket



- Bucket area = **longitudinal Acceptance** [eVs]
- Bunch area = **longitudinal beam emittance** = $\pi.\Delta E.\Delta t/4$ **[eVs]**

What About Beyond Transition

- Until now we have seen how things look like below transition

Higher energy ⇨ faster orbit ⇨ higher F_{rev} ⇨ next time particle will be **earlier**.

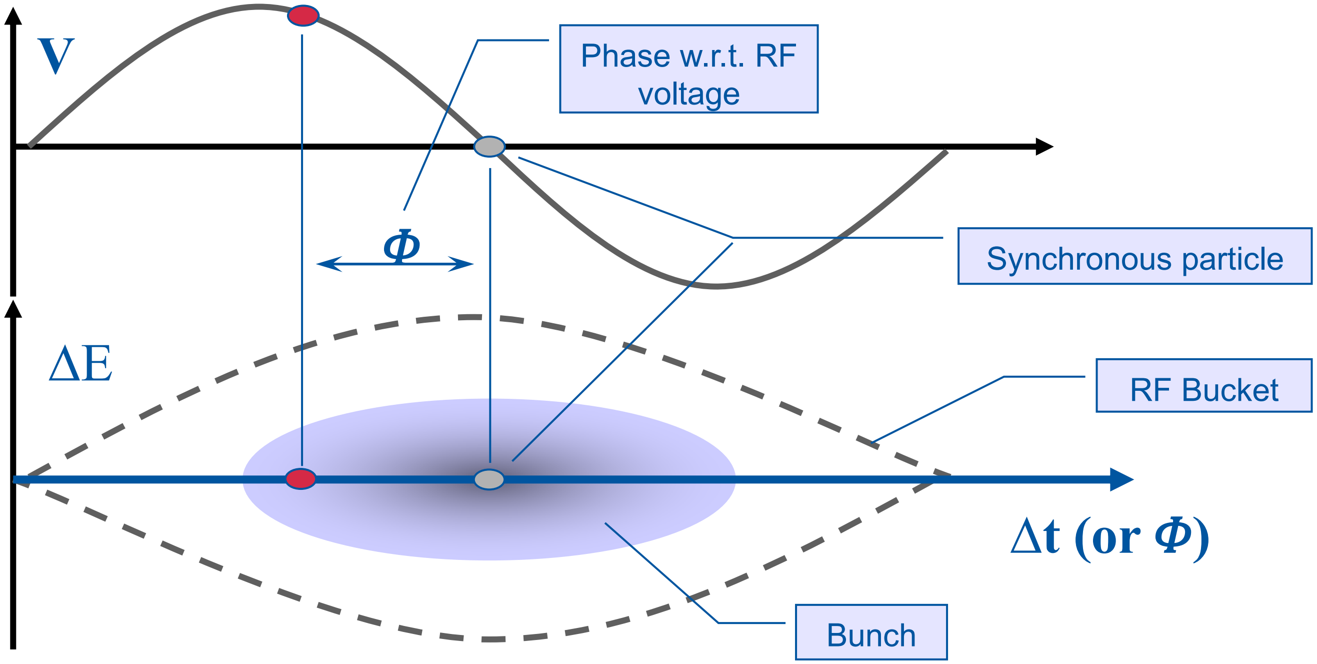
Lower energy ⇨ slower orbit ⇨ lower F_{rev} ⇨ next time particle will be **later**.

- What will happen above transition ?

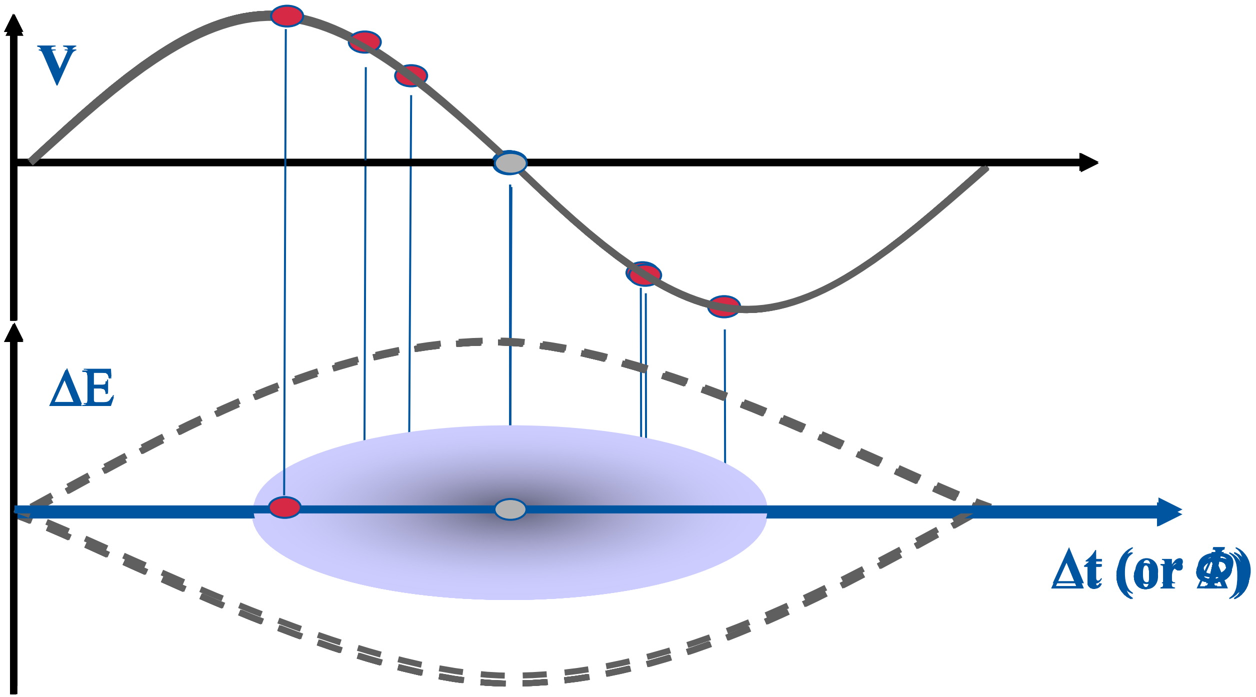
Higher energy ⇨ longer orbit ⇨ lower F_{rev} ⇨ next time particle will be **later**.

Lower energy ⇨ shorter orbit ⇨ higher F_{rev} ⇨ next time particle will be **earlier**.

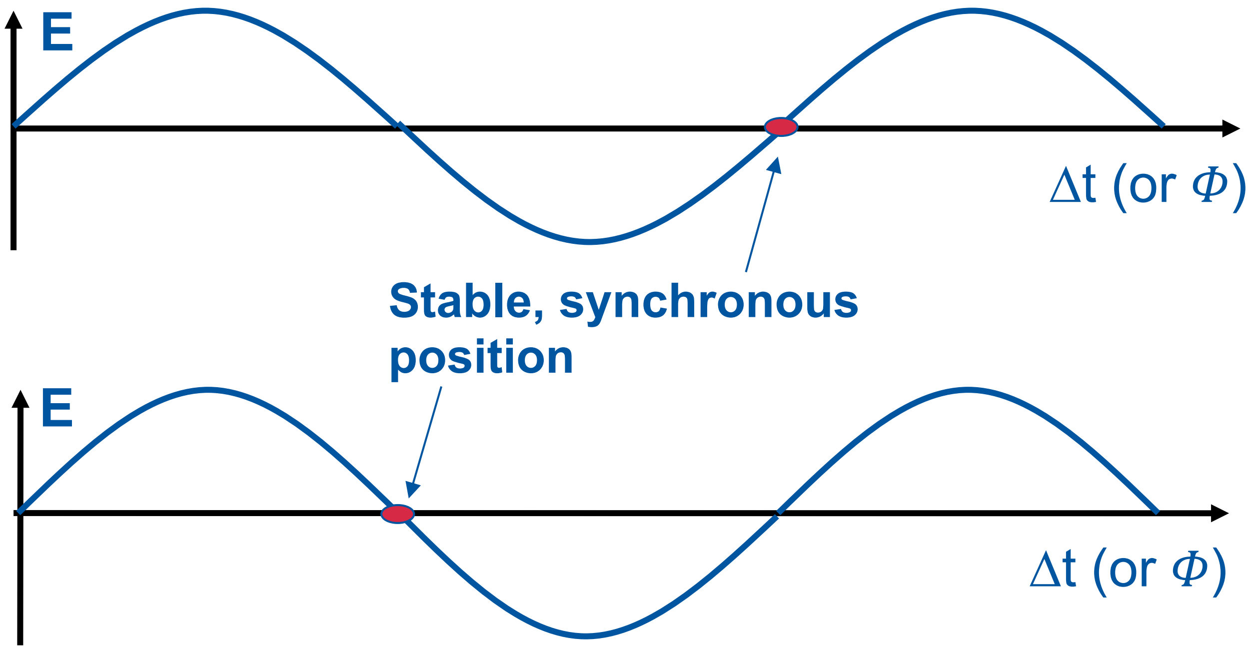
Longitudinal Motion Beyond Transition



Longitudinal Motion Beyond Transition



Before & After Transition

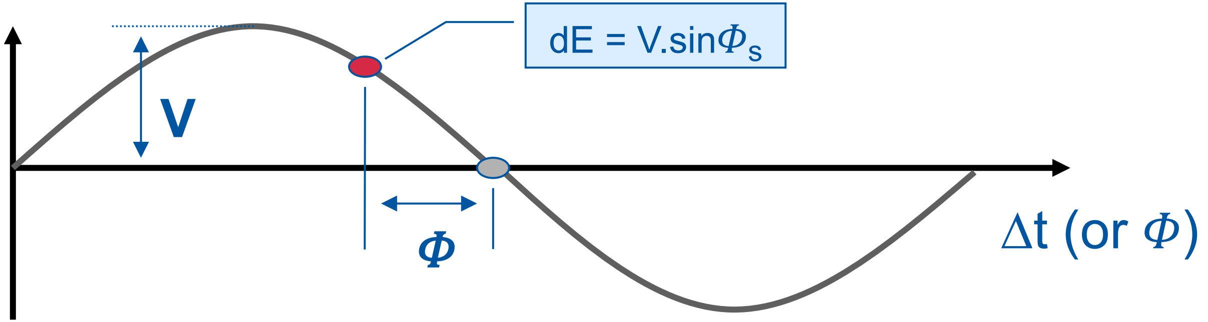


Before transition

After transition

Acceleration

- Increase the magnetic field slightly.
- The particles will follow a shorter orbit. (**f_{rev} < f_{synch}**)
- Beyond transition, early arrival in the cavity causes a gain in energy each turn.



- We change the phase of the cavity such that the new synchronous particle is at Φ_s and therefore always sees an accelerating voltage
- $V_s = V\sin\Phi_s = V\Gamma$ = energy gain/turn = dE

Harmonic RF Voltage - Multiple bunches

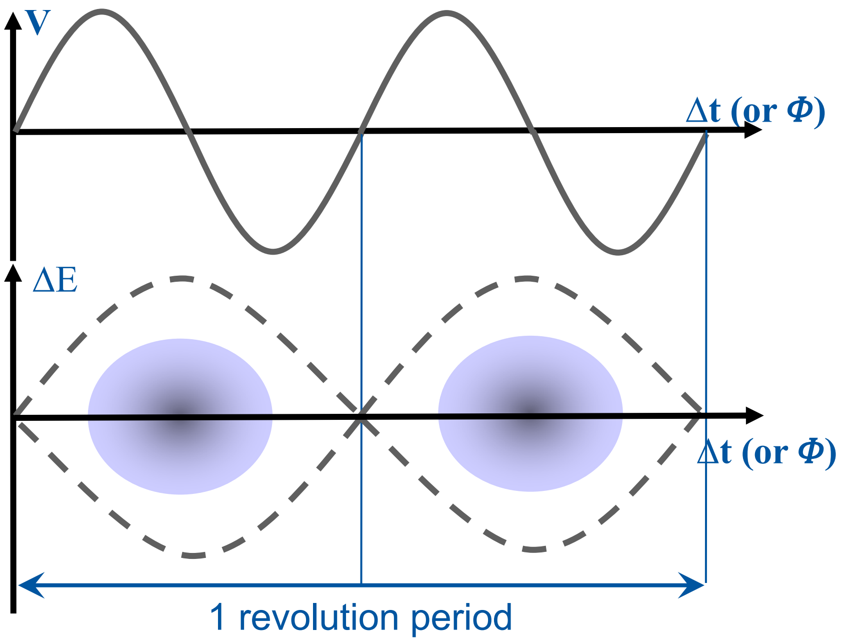
- Until now we have applied an oscillating voltage with a frequency equal to the revolution frequency

$$\boxed{f_{rf} = f_{rev}}$$

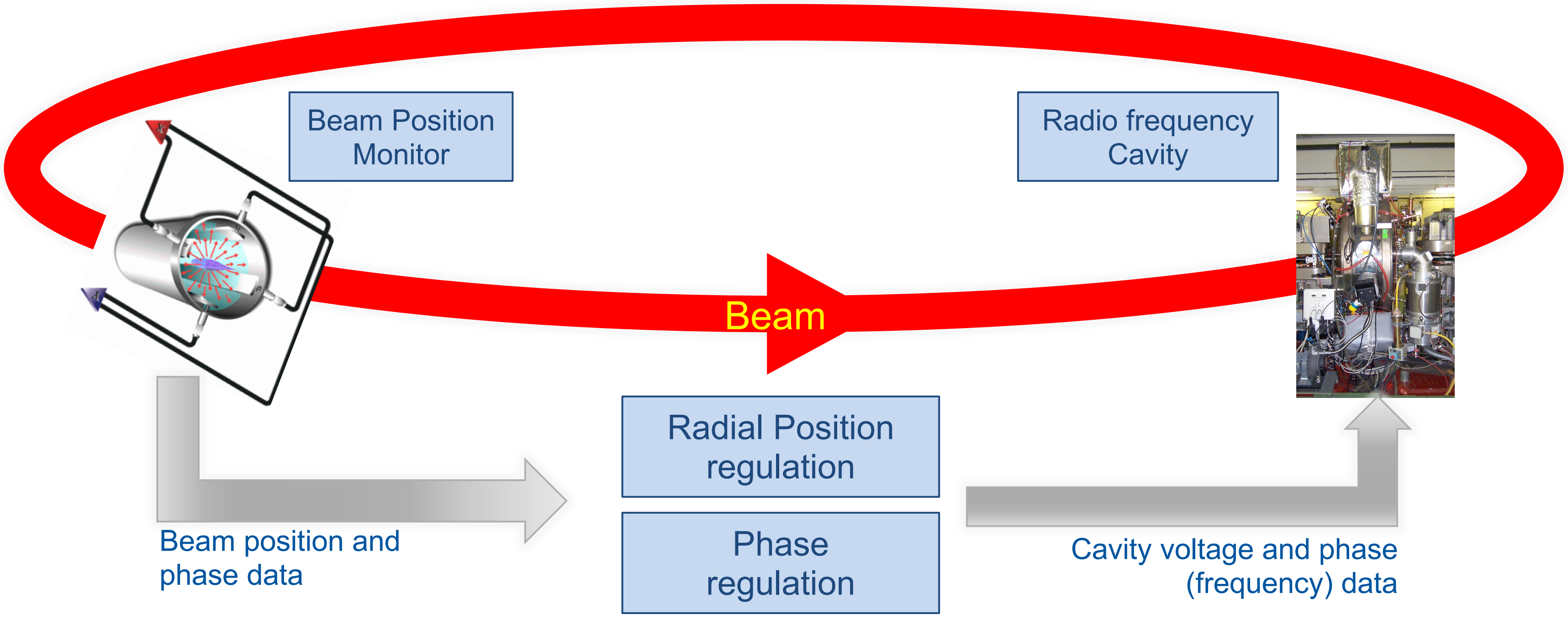
- Applying an f_{rf} which is a multiple of f_{rev} gives

$$\boxed{f_{rf} = h\, f_{rev}}$$

RF harmonic 2 case



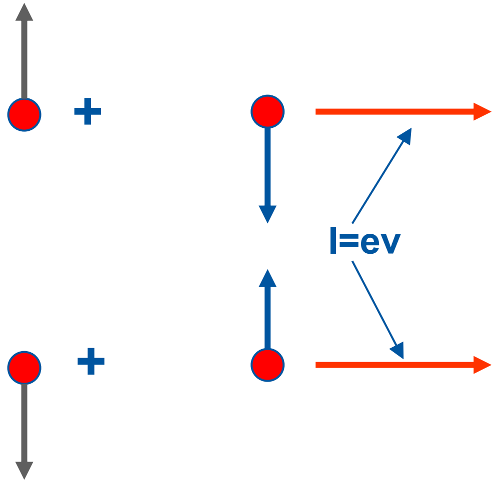
RF Beam Control



Some of the Possible Limitations

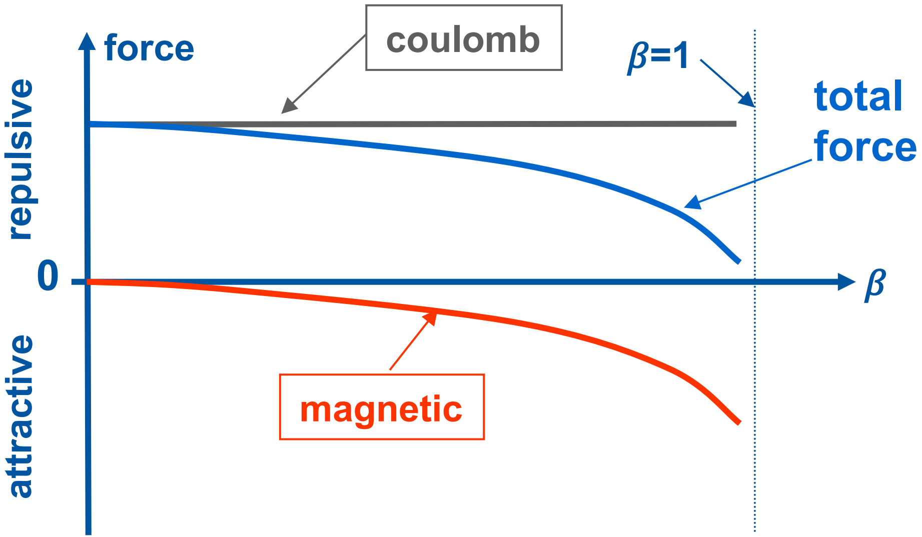
Space Charge

- Between two charged particles in a beam we have different forces:



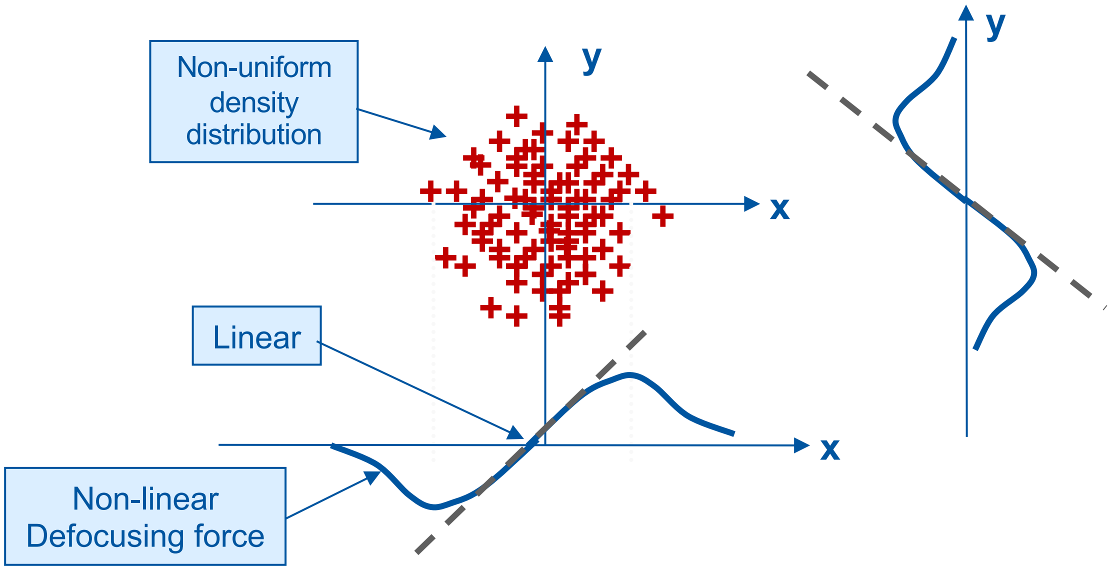
Coulomb repulsion

Magnetic attraction



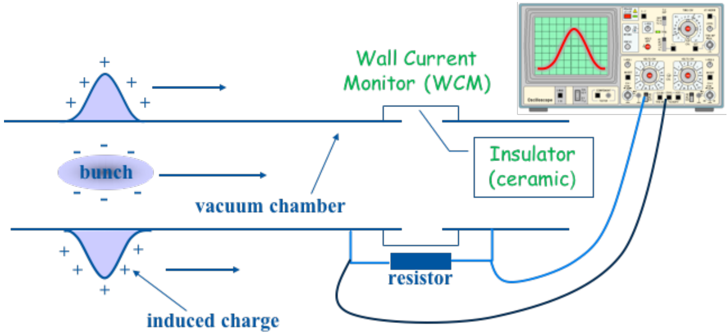
Space Charge

- At low energies, which means $\beta \ll 1$, the force is mainly repulsive $\Rightarrow$ defocusing
- It is zero at the centre of the beam and maximum at the edge of the beam

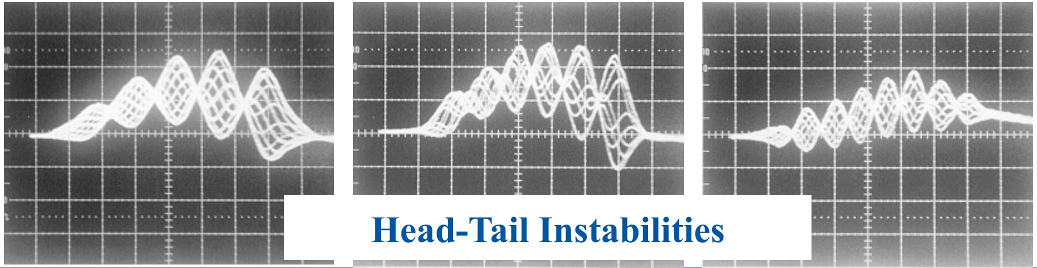


Collective Effects

- Induced currents in the vacuum chamber (impedance) can result in electric and magnetic fields acting back on the bunch or beam

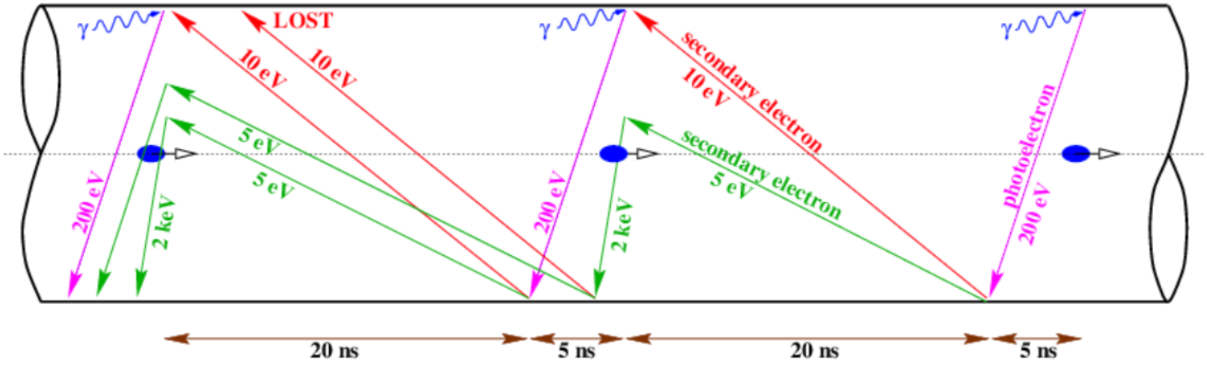


Coupled Bunch Instabilities



Head-Tail Instabilities

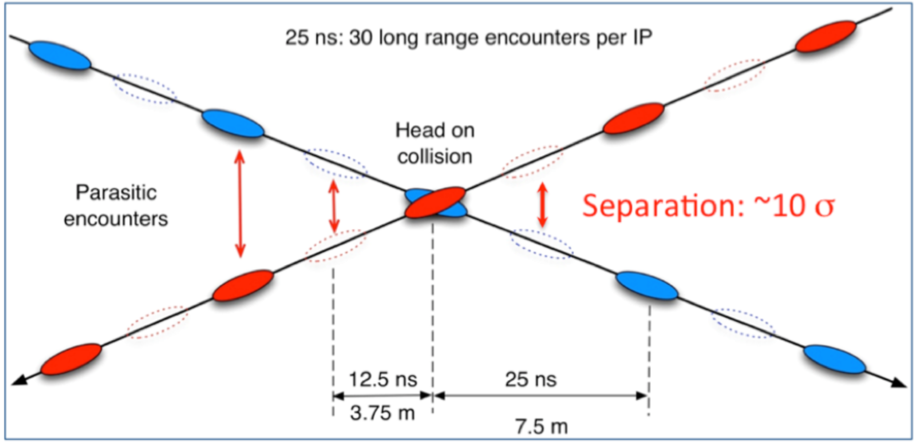
Electron Cloud



- e-cloud when SEY is beyond 2, hence it depends on the vacuum chamber surface
- The electron cloud forms an impedance to the beam and can cause beam instability
- In the SPS and the LHC we use the “scrubbing” method to reduce the SEY
- The SPS vacuum chambers will be Carbon coated to reduce the SEY

Beam-Beam Effect & Crossing Angle

- Particle beam are surrounded by magnetic fields
- If the beams “see” each other in colliders these magnetic fields can act on the both beams



- The strength of this action depends on:
  - The beam intensity
  - The distance between the beams

On they Way to HL-LHC…

LHC Luminosity, the Figure of Merit

$$\mathcal{L} = \frac{N_{events}/_{second}}{\sigma_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi \sigma_x \sigma_y} \mathcal{F}$$

Intensity per bunch

Number of bunches

Geometrical correction factors

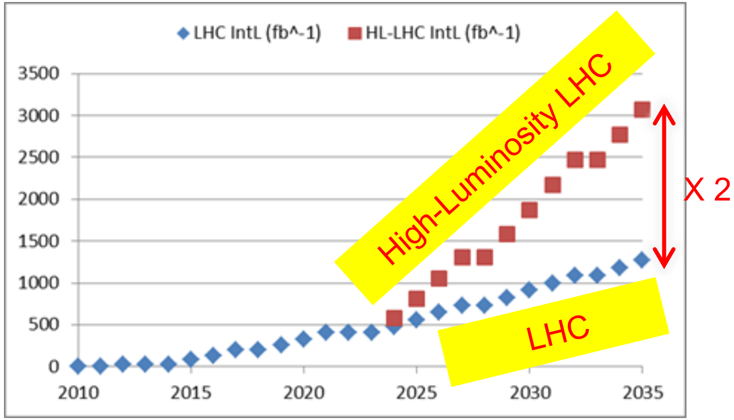
Beam dimensions

Fixed parameters:

- Revolution frequency
- Number of bunches

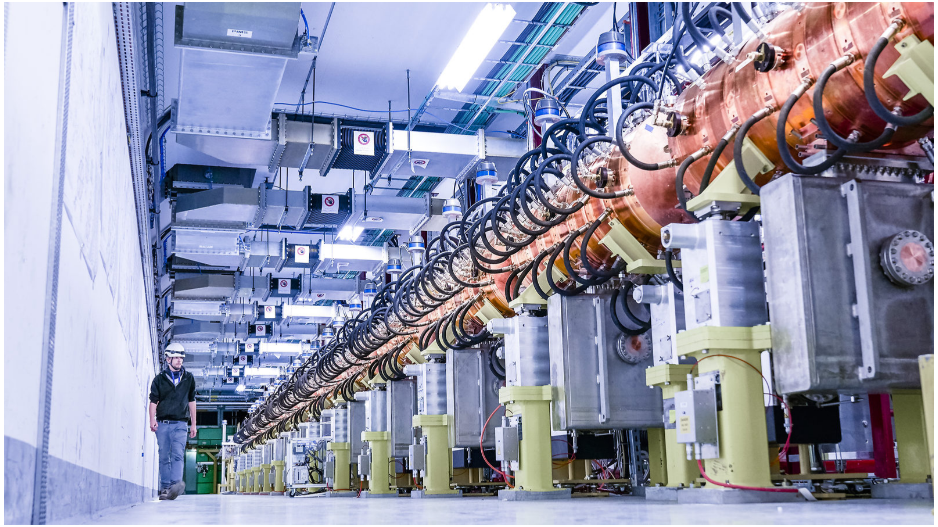
Parameters to optimize:

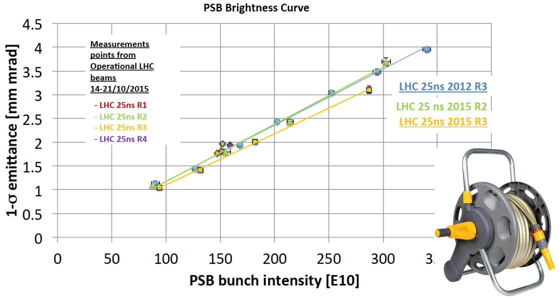
- Intensity per bunch
- Transverse beam dimensions
- Geometrical correction factors

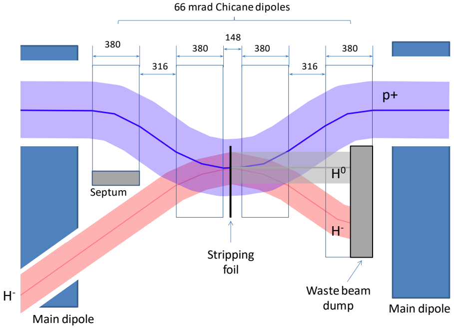


Linac 4, a key ingredient for LIU

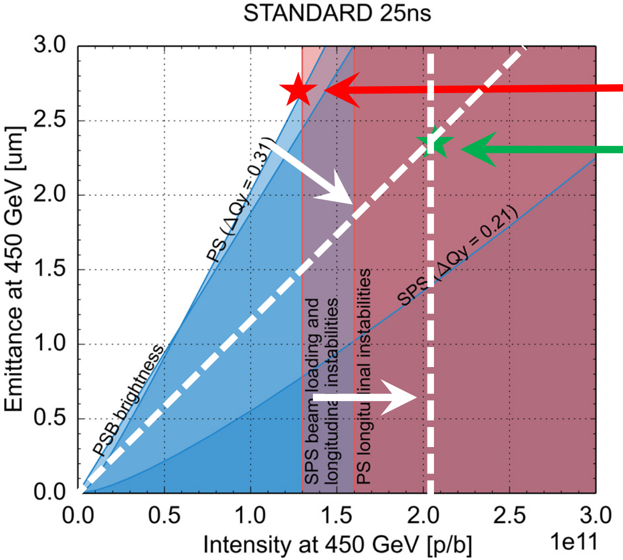
Brighter beams from the injectors chain







Injector Limitations Lifted



LHC Beam	Nb [x10^{11} ppb]	$\varepsilon_{x,y}$ [μm]
Present	1.3	2.7
HL-LHC target	2.3	2.1

- Increase brightness limit for PSB and PS with H^- injection and increase of injection energy

- Reduce longitudinal dipolar coupled bunch instability in PS that limits bunch intensity (Longitudinal damper/feedback)
- Increase RF power in the SPS and reduce coupled bunch instability that limits bunch intensity (add 800 MHz RF and impedance reduction)

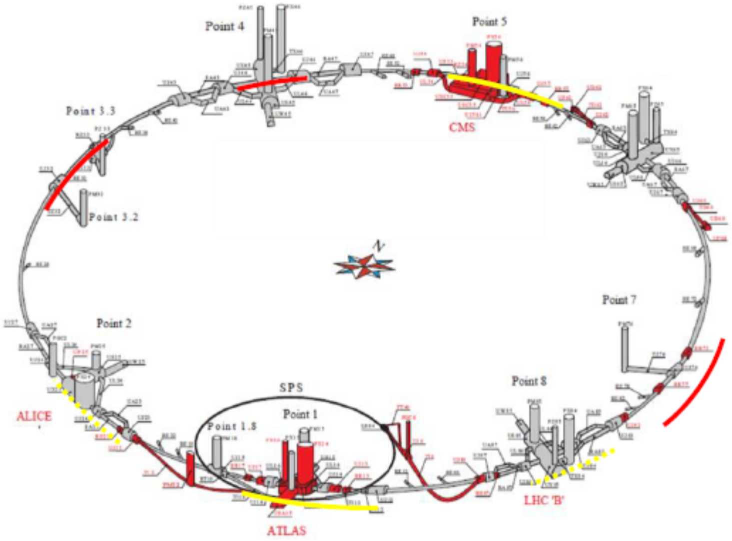
The aim of HL-LHC

- Peak luminosity of $L = 2\times10^{35}$ $cm^{-2}s^{-1}$
- Levelled luminosity of $L_{levelled}$ = **5×10^{34} $cm^{-2}s^{-1}$**
- This should allow for:
    - An integrated luminosity of **250 fb^{-1} per year**, with the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime

The stored energy in a single beam will increase from **~300 MJ** to **600 MJ**

HL-LHC: What will be changed ?

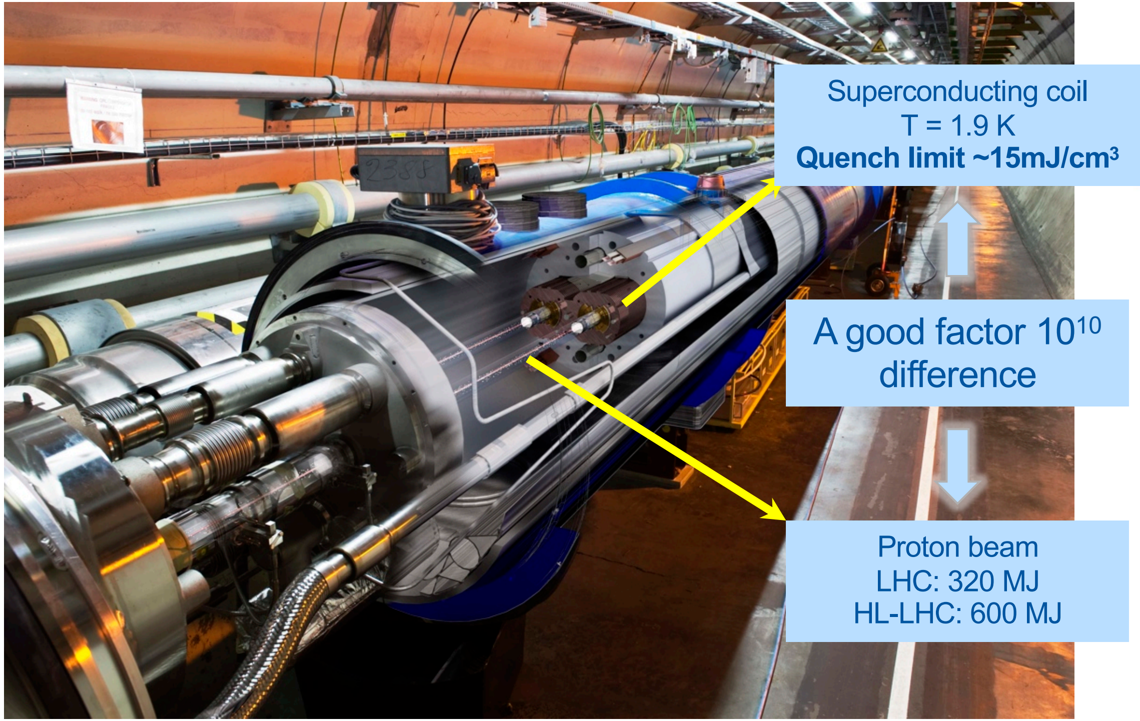


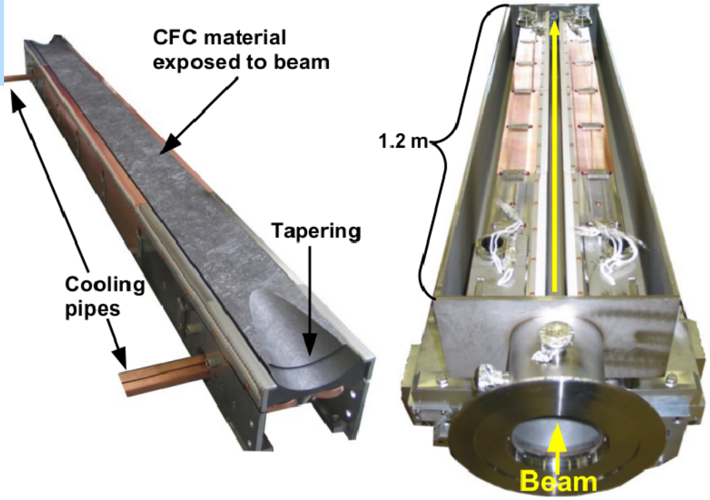
- New IR-quads (inner triplets)
- New 11T short dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC, these are only the main modifications and this list is not exhaustive

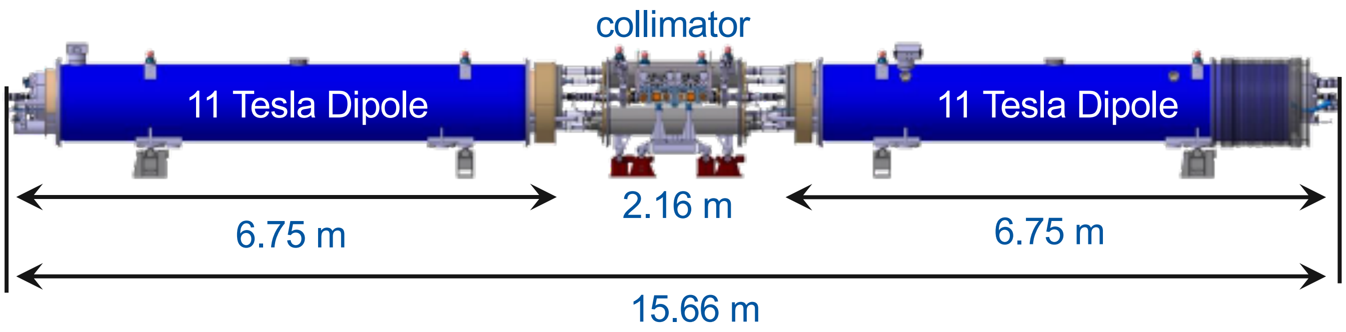
Just a very few selected items in the next slides

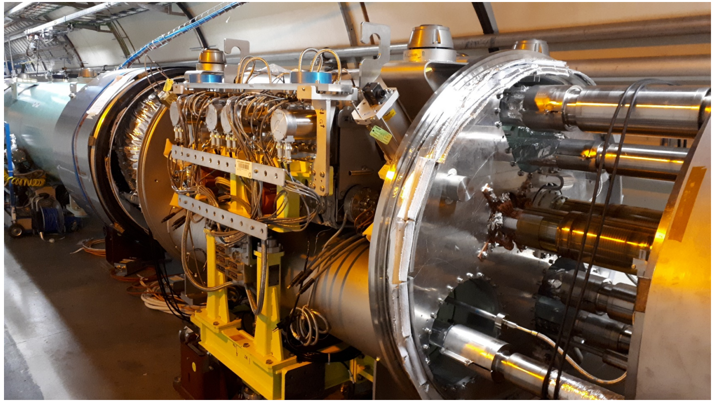
Need for Collimation (protection)





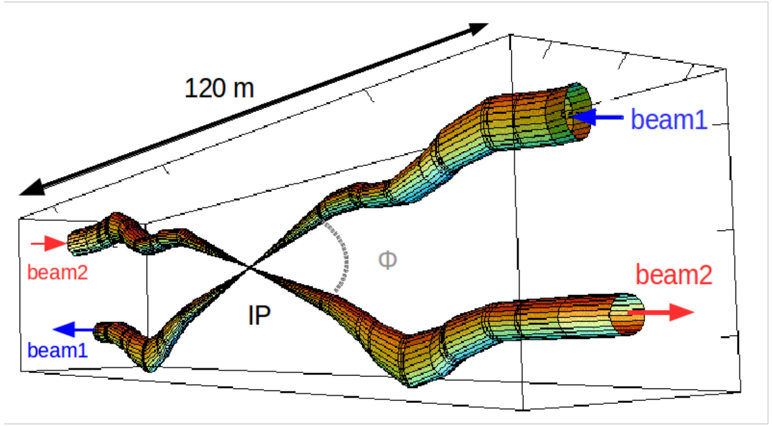
11 Tesla dipoles to Install Collimators



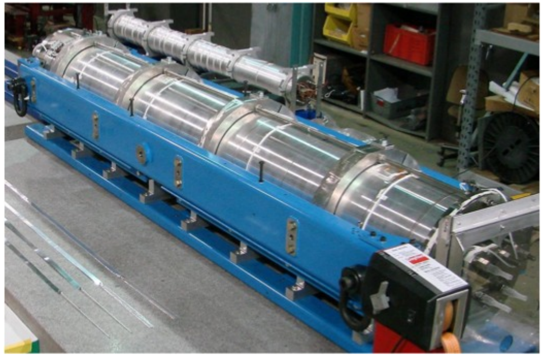


IR Quadrupoles (Inner Triplet)

- Aim: reduce β* from 0.4m or 0.3m to 0.1m or even lower.
- International R&D effort (USA & Europe)
- New material: Nb_3Sn instead of NbTi



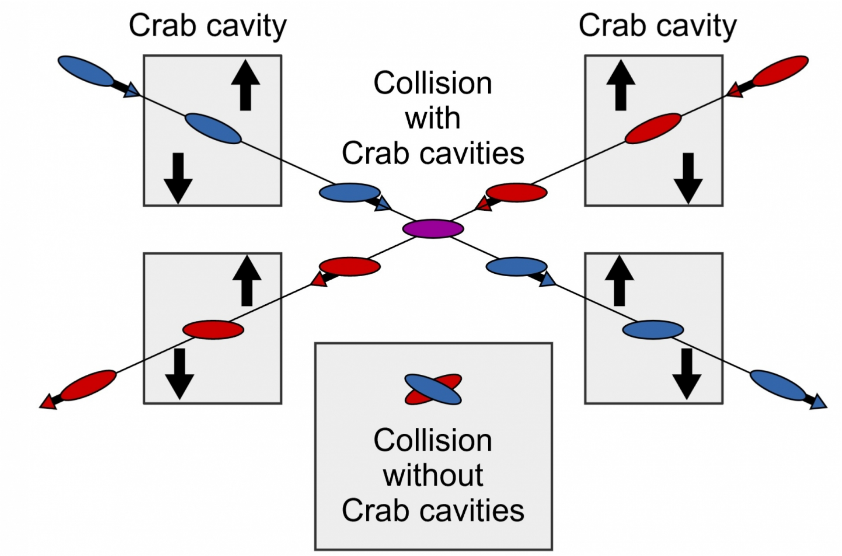
- Main requirements:
  - **Aperture 120 mm**
  - Gradient 200 T/m
  - **Peak field ~ 13 T**
- Presently in LHC:
  - **Aperture 70 mm**
  - **Peak filed ~ 8 T**

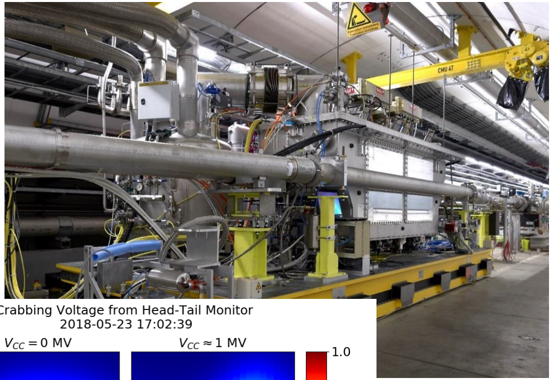


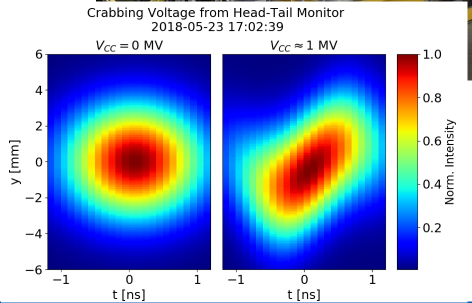
- The HL-LHC IR-Quadrupole design and R&D is a key stepping stone for future high-field applications

Crossing Angle and Crab Cavities

- Increased beam-beam effect in LHC with higher beam intensity
  - Requires increase of the crossing angle, hence reduction of the geometrical factor





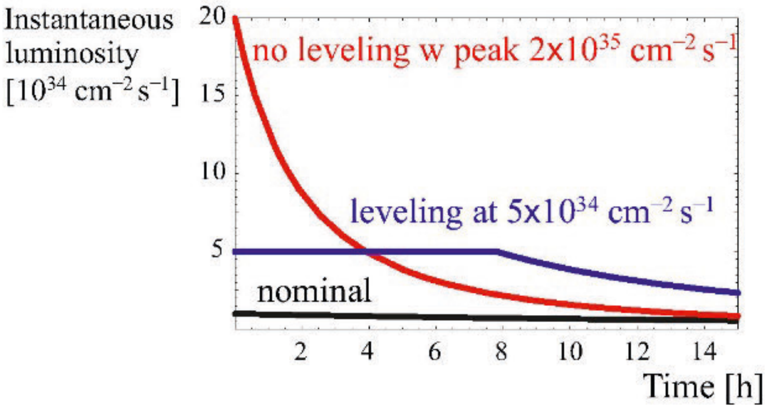


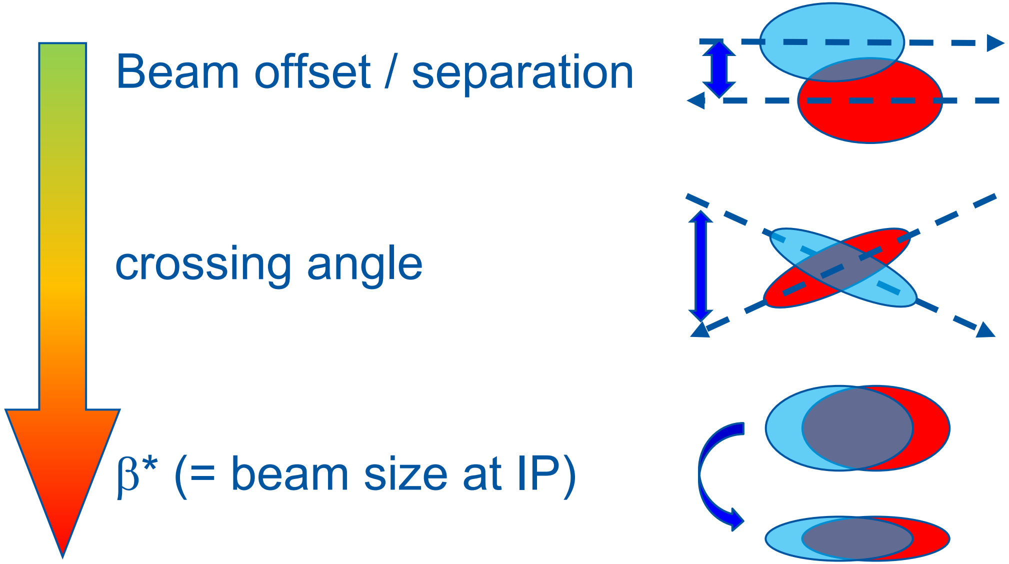
World' s first crabbing on a proton beam (23 May 2018)

Levelling & Anti-levelling – preparing for HL-LHC

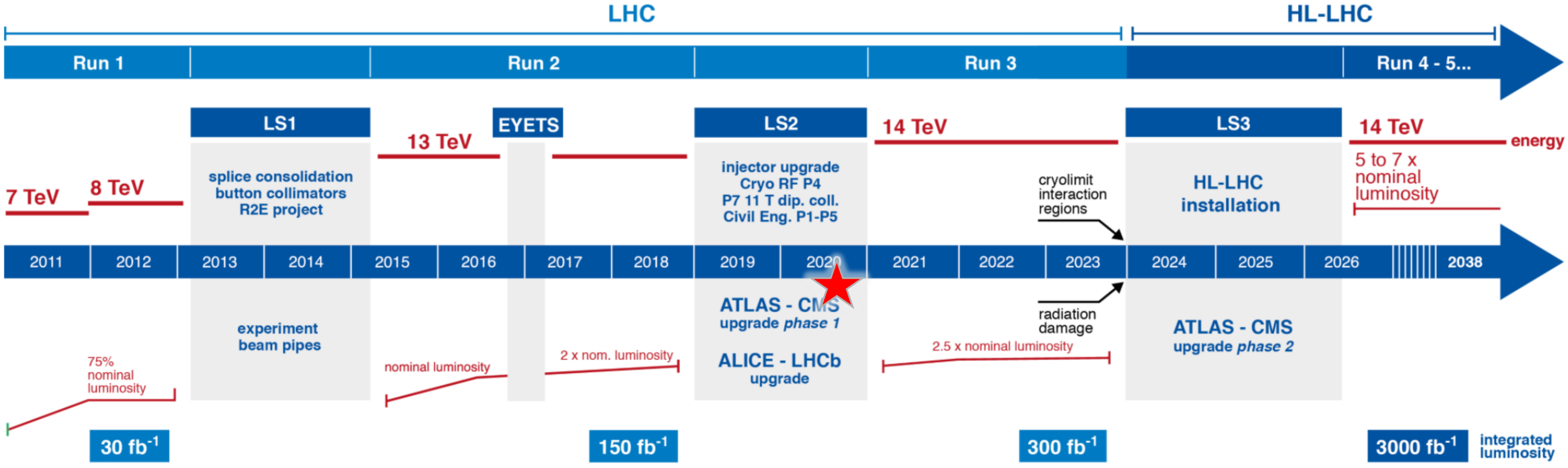
- In certain conditions and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – **levelling**.

Levelling for HL-LHC





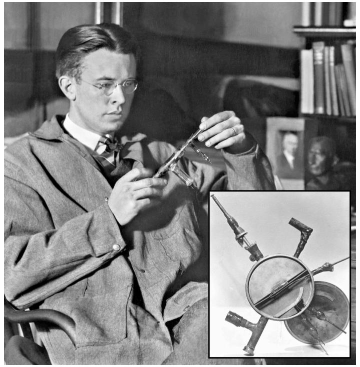
Planning



- Recently start LS3 was shifted from 2024 to 2025
- Following the Covid-19 pendemic this is being revisited, especially 2020/2021

"We shall have no better conditions in the future if we are satisfied with all those which we have at present."

Thomas A. Edison
Inventor and businessman, 1874 – 1931



E. Lawrence who invented the cyclotron in 1929

The LHC Today

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Synchrotron Oscillation

- On each turn the phase, ***Φ***, of a particle w.r.t. the RF waveform changes due to the synchrotron oscillations.

$$\frac{d\phi}{dt} = 2\pi h \Delta f_{rev}$$

Change in revolution frequency

Harmonic number

- We know that $\frac{df_{rev}}{f_{rev}} = -\eta \frac{dE}{E}$

- Combining this with the above $\therefore \frac{d\phi}{dt} = \frac{-2\pi h \eta}{E} \cdot dE \cdot f_{rev}$

- This can be written as: $\boxed{\frac{d^2\phi}{dt^2} = \frac{-2\pi h \eta}{E} \cdot f_{rev} \cdot \frac{dE}{dt}}$

Change of energy as a function of time

Synchrotron Oscillation

$$\frac{d^2\phi}{dt^2} = \frac{-2\pi h\eta}{E} \cdot f_{rev} \cdot \frac{dE}{dt}$$

and

$$dE = V \sin\phi \longrightarrow \frac{dE}{dt} = f_{rev} V \sin\phi$$

$$\frac{d^2\phi}{dt^2} = \frac{-2\pi h\eta}{E} \cdot f_{rev}{}^2 \cdot V.\sin\phi$$

- If Φ is small then **sinΦ=Φ**

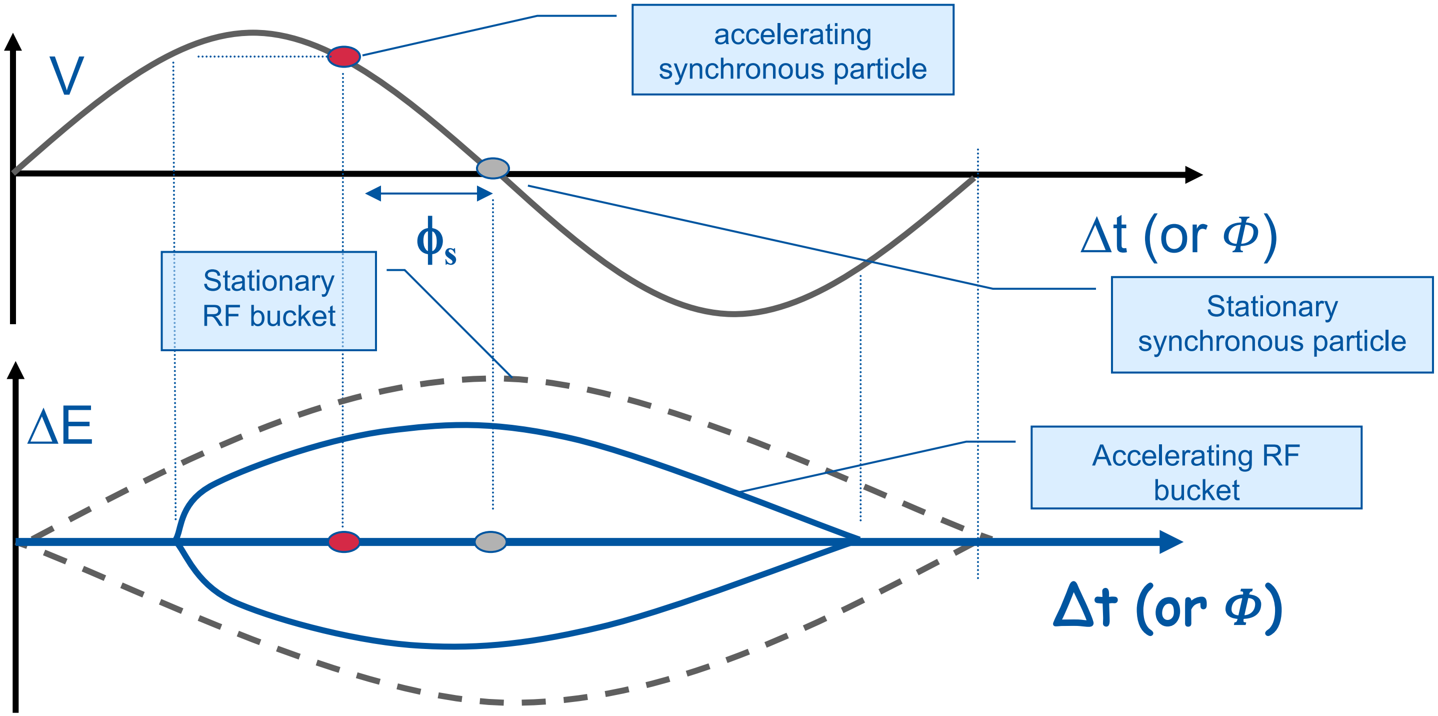
$$\frac{d^2\phi}{dt^2} + \left(\frac{2\pi h\eta}{E} \cdot f_{rev}{}^2 \cdot V\right)\phi = 0$$

- This is a SHM where the synchrotron oscillation frequency is given by:

$$\left(\sqrt{\frac{2\pi h\eta V}{E}}\right) \cdot f_{rev}$$

Synchrotron tune Qs

Accelerating Bucket



Accelerating Bucket

- The modification of the RF bucket reduces the acceptance
- The faster we accelerate (increasing sin Φ_s) the smaller the acceptance
- Faster acceleration also modifies the synchrotron tune.

- For a stationary bucket ($\Phi s = 0$) we had: $$\left(\sqrt{\frac{2\pi h\eta}{E}}\right)\cdot f_{rev}$$

- For a moving bucket ($\Phi s \neq 0$) this becomes: $$\left(\sqrt{\frac{2\pi h\eta}{E}}\right)\cdot f_{rev}\cos\phi_s$$

LHC & HL-LHC Parameters

Parameter	LHC	LHC 2018	HL-LHC	HL-LHC
Beam type:	Design	BCMS	Design Stand.	Design BCMS
Energy [TeV]	7	6.5	7	7
Number of bunches per ring	2808	2556	2748	2604
Bunch spacing [ns]	25	25	25	25
Bunch population N_b [10^{11} p/b]	1.15	1.1	2.2	2.2
Transv. norm. emittance SB ε_n [mm mrad]	3.75	2	2.5	2.5
Betatron function at IP1 and IP5 β^* [m]	0.55	0.3/0.25[2]	0.2 (0.15)	0.2 (0.15)
Half crossing angle in IP1/5 [μrad]	142.5	160/130[1]	260	260
Geometrical factor w/o crab cavities at min. β^*	0.836	-	0.369	0.369
Geometrical factor with crab cavities at min. β^*	-	-	0.715	0.715
Peak Luminosity w/o crab cavities [10^{34} cm^{-2}s^{-1}]	1	2.1	6.52	6.18
Peak luminosity with crab cavities [10^{34} cm^{-2}s^{-1}]	-	-	12.6	11.9
Levelled luminosity [10^{34} cm^{-2}s^{-1}]	-	-	5.32	5.02
Expected levelling time [h]	-	-	5.23	5.23
Events/crossing μ (with levelling & crab cavtities)	~25	~60	140	140
Stored beam energy [MJ]	360	320	675	640